

# RADIATION DAMAGE SHIELDING OF SOLAR CELLS ON A SYNCHRONOUS SPACECRAFT

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## ABSTRACT

The ATS-I synchronous spacecraft (altitude 22,240 miles, launched Dec. 6, 1966) carried a group of conventional n-on-p, 10 ohm-cm, silicon, boron-doped solar cells with various radiation shields. The shields were, mostly, of Corning type 7940 artificial fused silica, of thicknesses from zero to 60 thousandths of an inch.

The solar cell damage observed, as deduced from voltage-current curves, was larger than expected. The maximum power from cells bearing shields of 0, 1, 6, 15, 30, and 60 thousandths of an inch in thickness fell, during 416.8 days in orbit, to 11.4, 84.9, 92.5, 88.7, 86.9, and 83.5 percent of initial values, respectively. The short-circuit currents fell to 41.4, 90.1, 91.7, 92.7, 92.6, and 93.9 percent, respectively. The open-circuit voltages fell to 55.0, 97.2, 98.9, 98.7, 98.7, and 98.3 percent, respectively.

Thus, unexpectedly, under the conditions of this experiment, shields of 6 thousandths of an inch thickness provided greater power protection than either thicker or thinner shields. In addition to penetrating particle damage, it is indicated that some loss of illumination occurred, and some internal series resistance developed, especially in the more heavily shielded cells.

## INTRODUCTION

The use of solar cells on unmanned spacecraft to provide electric power for communication and experiment purposes is almost universal. These devices, which convert solar energy directly to electric power with an initial efficiency of about 10 percent, suffer radiation damage in space. The damage is ordinarily ascribed to bombardment by electrons and protons trapped in the earth's magnetic field (the "Van Allen belts"). It is important to develop types of solar cells, with suitable transparent radiation shields, which minimize this damage. While laboratory damage studies using particle accelerators have been very helpful, the full space environment cannot conveniently be simulated. This report will give some results from a space experiment carried aboard the ATS-I spacecraft. The complete voltage-current characteristics of the experimental solar cells were telemetered to ground. This allowed judgment of the cells' condition in exceptional detail. In this partial report the results from

the group of cells in which shield thickness was varied will be reported.

Among other experimenters who have conducted orbital radiation damage experiments are Longenecker<sup>1</sup>, Reynard<sup>2</sup>, and Fischell<sup>3</sup>. The author<sup>4,5</sup> has previously reported measurements on Relay I and Relay II. In all of these studies the orbits were moderately or highly damaging, much more so than the synchronous equatorial one of ATS-I. The solar cells flown in previous experiments were older p-on-n, and n-on-p silicon and gallium arsenide types. Shield materials were glass, sapphire, and fused silica, of thicknesses from zero to 80 mils (thousandth of an inch). To develop signal voltages large enough for convenient telemetry a number of cells were often connected in series and fairly large load resistors were employed. It was usually intended that the cell property being monitored was short-circuit current, although the maximum power was approximated in one case<sup>1</sup>. There was agreement, however, that the damage to the cell property measured decreased monotonically with increase in shield thickness in these experiments. It may be concluded that when the environment is the highly damaging one of the conventional "belts" thick shields protect short-circuit current and, probably, maximum power. In the low damage rate environment at synchronous altitude, however, shielding considerations do not seem to be so straightforward, as will be shown later.

The purpose of this report is to present certain of the data obtained from the ATS-I solar cell radiation damage experiment and to suggest possible explanations of the observed results.

## THE ATS-I RADIATION DAMAGE EXPERIMENT

The ATS-I spacecraft was launched from Cape Kennedy on Dec. 7, 1966, at 2 hours, 12 minutes, GMT. It carried, with other experiments, this experiment on solar cell radiation damage. The spacecraft executed one and one-half transfer ellipses (perigee: 100 miles; apogee: 23,000 miles; time: 15 hours) before entering its final circular, near-synchronous equatorial orbit at 22,240 miles altitude. The final station was over the Pacific equator at 157 degrees west longitude. The spacecraft was spin stabilized at about 100 rpm.

## The ATS-I Apparatus

The radiation damage experiment on board involved 30 solar cells of various kinds, bearing various shields. Sophisticated circuitry, including a 2176 bit magnetic memory, allowed transmission of each cell's terminal voltage, while loaded successively with eight load resistors (about 3, 4.5, 6, 8, 10, 25, and 2000 ohms). The voltages were evaluated on board, at maximum illumination, by an 8 bit analog-to-digital converter (capacity: 255 units for 765 mv, or 3 mv per bit) and stored in the memory for subsequent digital PFM telemetry. Also transmitted were responses to calibrating voltages of 0.0 and 480.0 mv, a solar cell temperature reading, the angle of incidence of the illumination, cell identification and time of observation. The telemetry signals were recorded on the ground on magnetic tape. The magnetic memory was re-filled several times a day in response to ground commands. Earlier reports<sup>6,7</sup> on results from this experiment were based on a rapid computer analysis of the data. For this report some of the data have been hand recomputed with a calculator with all calibrations and corrections being applied with great care. The readings also have been corrected to a common temperature. At this point, the general conclusions previously reached have not been changed by the improved computations here employed. Numerical values are, however, slightly changed.

The panel carrying the solar cells was 4 by 8 inches in size. It was made of one-eighth inch thick magnesium, for temperature uniformity. Temperature was measured at the center point only. The apparatus weighed 5 pounds and consumed 5 watts.

### Calibration

Certain calibrations were performed before launch. The solar cell damage panel was exposed to the sun (about 90 mw/cm<sup>2</sup>) through a 6 foot collimator to exclude skylight. The response of each cell as loaded by each load resistor was then x-y recorded versus angle of incidence. The stray resistances in the solar cell leads were evaluated. The thermistor was carefully calibrated versus temperature. The analog-to-digital converter was adjusted for zero, linearity, and slope.

### The Solar Cells

Results from 11 of the 30 solar cells will be reported here. These cells were all nominally 1 cm by 2 cm in size, 12 mils thick, silicon, boron-doped, and of about 10 ohm-cm base resistivity. It is believed that these cells were typical of "modern" solar cell technology. There were pairs of cells bearing shields of 0, 1, 6, 15, 30, and 60 mils thickness. The 1 mil shields were of an "integral" type<sup>8</sup> (7740 glass powder melted to cover the cells). They had no shield adhesive or surface anti-reflective coating. The other cells bore shields of Corning type 7940 ultraviolet resistant, artificial fused silica, attached with Dow-Corning type XR-6-3488 adhesive. These shields had blue rejection filters with a 400 milli-micron cut-off to avoid adhesive darkening. Silicon monoxide anti-

reflective coatings were also present on the surface of these cells.

### Data Corrections

Each telemetered solar cell response was corrected to the value it presumably would have had if the illumination had been normal to the surface. Angles of incidence varied from zero to 24 degrees and were measured in orbit to one degree. The applicable correction functions were deduced from a pre-flight ground calibration made for this purpose. The empirical functions could not be adequately represented by the usual  $1/\cos \phi$  relation, even near short-circuit current. They departed more widely from this form at other points on the cell characteristic curve.

A second correction was applied to bring the results to those corresponding to a satellite-sun distance of one astronomical unit (about 140 mw/cm<sup>2</sup>). It was based on daily predictions of the actual distance, and the inverse square law. This correction had a maximum value of about 3.3 percent.

A final correction was made to bring the results to those expected at a temperature of 24.4°C. The temperature coefficient of the voltage coordinate of a data point was determined, for each cell, from in-flight observations of the cell's open-circuit voltage as temperature changed. A temperature coefficient of current whose value was 0.0758 ma/°C was provided by Slifer<sup>9</sup> from measurements on 10 ohm-cm cells. For the data in this report the maximum temperature correction was for a temperature deviation of only 5.4°C.

No corrections were found necessary for telemetry zero on gain. Such changes were barely detectable.

The final voltage-current curves were drawn by eye as best fit to the eight points available. Maximum power points were located with the aid of an overlay of constant power curves. The data are extremely regular.

### Results

Table I is a numerical summary of the results of this part of the experiment. Important characteristics of the solar cells are given at five different times after lift-off. Columns 5, 6, and 7 show values (averaged over the two cells of a pair) of short-circuit current, open-circuit voltage, and maximum power. Column 8 shows the average value of the "curve factor" (F). This factor is the ratio of the maximum power to the product of short-circuit current and open-circuit voltage. Columns 9, 10, and 11 give the average short-circuit current, open-circuit voltage, and maximum power as percentages of initial values. The latter were those obtained in orbit 0.064 days after lift-off. It is believed that little, if any, damage to these cells had occurred up to this time. All table values were read from voltage-current curves that had been corrected to 24.4°C, one astronomical unit distance, and normal illumination. Quantities in parentheses

are uncertain because they were based on extrapolated values for short-circuit current.

Fig. 1 shows the voltage-current characteristics of cell 25 at different times after lift-off. This is a "modern" 10 ohm-cm silicon cell with no shield. The maximum power point is indicated on each curve. In some cases part of the curve has been estimated, as shown by a dashed region. The characteristics of cell 26, a similar cell with no shield, were almost identical with those of cell 25 over the great range of radiation damage encountered.

Cells 15 and 16 were those having integral 1 mil shields. Their averaged curves are shown in Fig. 2, which includes all (corrected) data points. The consistency of the data and the similar degradation of the cells are evident.

In Fig. 3 are shown a pair of curves for cell 5, which bore a 6 mil shield. Cell 6 gave very similar results.

Cell 20 (Fig. 4) bore the thickest shield (60 mils). Returns from companion cell 19 failed early in the experiment, presumably because of failure in the switching circuitry, which involved 80 micro-miniature relays, their transistor drivers, and address circuitry.

Curves for the 15 and 30 mil shielded cells are not shown, but were intermediate between those of Figs. 3 and 4.

The manner in which the maximum power from some of these cells deteriorated with time in orbit is shown in Fig. 5, while Fig. 6 shows the virtue of various thicknesses of shields in protecting several important solar cell properties. The bars on these curves terminate at the data points for the two cells of the pair on which measurements were made.

#### Discussion

It is readily evident from Table I and the Figures that the solar cells covered in this report deteriorated very significantly in the 416 days in synchronous orbit. I will not attempt here to quantitatively compare these results with damage predictions based on measured solar cell properties and what is known about the particle environment at an altitude of 22,240 miles. Suffice it to say, that a number of workers and organizations actively engaged in designing spacecraft for extended use, commercial or otherwise, at synchronous altitude consider the amount of damage here found to be significantly longer than anticipated. According to Brown<sup>10</sup> the main solar array on ATS-I also degraded much more than expected during the time here considered, supporting these experimental results.

We will attempt, below, to suggest the causes of the observed solar cell damage and the equivalent circuit elements affected. It is intended that this qualitative analysis will be later followed by a further, more rigorous treatment.

Comparison of Figs. 1 and 2 reveals that shields of 1 mil of 7740 glass were very effective in stopping some highly damaging agent. This shield (about 5.7 mg/cm<sup>2</sup>) was capable of stopping protons whose energies were up to 1.5 MeV. It would have practically no effect on electrons. Thus, the excluded particles were doubtless low energy protons. Conversely, these were the damaging agents on unshielded cells 25 and 26. It is known that there is considerable population of such protons at synchronous altitude.

A daily plot of the short-circuit current of cell 25 showed that degradation occurred largely by way of a number of discrete steps, usually requiring several days per step. Now, on board ATS-I there were electron and proton detectors. According to Paulikas<sup>11</sup> the times and durations of the above unshielded solar cell degradation steps correlate very well with his detection of solar flares, in which solar protons struck the spacecraft. A particularly large flare and damage step occurred between 166 and 174 days in orbit, or days 142 to 150 of year 1967. While the above proton detectors were effective only in the energy range from 5 MeV to 70 MeV there is little doubt that it was the low energy tail of the spectrum of solar protons which so heavily damaged these (and other) bare solar cells in this experiment. If other damage effects occurred they were minor, for the unshielded cells.

The solar flare proton damage steps were not apparent in the daily plot of the open circuit voltage of cell 25. Also, they were not evident in any cells shielded with 1 or more mils of material. The cause for the more gradual degradation of the shielded cells of this experiment must be sought elsewhere.

A number of laboratory damage curves for 10 ohm-cm resistivity solar cells have been made by Gdula<sup>12</sup>. The damaging agents were 300 KeV and 500 KeV protons, and 1 MeV electrons. He also has taken voltage-current curve sets in which intensity of illumination, and series and shunt resistance (simulated) were varied. These have proved valuable in suggesting, qualitatively, the origin or character of the solar cell damage in the space experiment.

Thus, it is found that the curves of Fig. 1, for 0.064 and 3.28 days exposure of an unshielded cell in orbit are similar to those obtained by Gdula using a 300 KeV proton beam. This suggests that the damage to the flight cells, during the first few days at least, was largely caused by low energy protons. These were doubtless encountered in the three passages through the trapped radiation belts during execution of the transfer ellipse. As mentioned above, solar flare protons caused almost all of the later damage. The strong solar proton flare that occurred about 170 days after lift-off was mainly responsible for the damage depicted in Fig. 1 as having occurred between 100.7 and 270.4 days after lift-off. Also, Fig. 1 indicates that cell 25 became extremely "hardened" against open-circuit voltage damage after about 100 days in orbit.

The 1 mil shielded cell curves of Fig. 2 seem best accounted for by postulating some damage by penetrating

electrons or protons, plus some loss in short-circuit current, as might have been caused by a diminution of the illumination.

Fig. 3 shows the degradation of a 6 mil shielded cell over 416 days in orbit. Again using the laboratory determined cell damage curves for reference it appears that this degradation may have been caused by a combination of a small amount of penetrating electron damage plus some loss of illumination.

In Fig. 4 we see an unusual pair of curves, for the 60 mil shielded cell. The open-circuit voltage degradation is about the same as for the 6 mil shielded cell (Fig. 3), the short-circuit current degradation is somewhat less (as if the thicker shield had afforded some added protection from penetrating particle damage), but a large and obvious degradation has occurred in the region of maximum power. I suggest that these effects may be accounted for by some particle damage, plus a moderate drop in illumination, and, in addition, some damaging agent particularly effective in the maximum power region. The laboratory reference curves suggest that either series or shunt resistance had been introduced by some means. Since shunt resistance also causes an obvious drop in open-circuit voltage (which is absent in Fig. 4) the introduction of series resistance seems likely. However, the choice depends critically on the behavior of open-circuit voltage. If it were incorrectly measured, or a temperature correction were in error, shunt resistance would be allowed.

Passing to Fig. 6 we see how increasing the shield thickness from 1 to 60 mils affected certain important solar cell properties, as evaluated after 416.8 days in orbit. As mentioned before, it is apparent that the thicker shields increasingly protected the cells from short-circuit current damage. This is consistent with the assumption that at least part of the cell damage observed in this experiment was caused by penetrating particles.

It is apparent from Fig. 6 that increasing the shield thickness beyond 6 mils provided no further significant protection of open-circuit voltage. This is consistent with the supposition that low energy protons (which affect this region critically) were almost completely excluded by shields of 6 mils, and greater. Such a shield stops protons of energy up to 4.3 MeV and electrons up to 0.175 MeV.

The maximum power curve of Fig. 6 is unusual. We have already seen from the discussion of Fig. 3 and 4 (involving 6 and 60 mil shields) that the thicker shield was associated with the greater power loss. It is evident from Fig. 6 that the 15 mil and 30 mil shields were associated with power losses of intermediate value. The alarming implication of the above is that, in the environment of this experiment, and, using conventional solar cells mounted and shielded in the customary manner, thicker shields not only do not provide the expected protection from environmental damage, they aggravate it. They are also, of course, heavier.

We further see that, in this experiment, short-circuit current was not a valid indicator of solar cell damage in the useful region of maximum power.

In Fig. 5 we see how the maximum power of certain indicated solar cells changed with time. The unshielded cells 25 and 26 degraded rapidly. It is believed that the degradation during the first day in orbit actually occurred in several steps, as the spacecraft passed repeatedly through the trapped radiation belts.

The Fig. 5 curves for the shielded cells show (as does Table I) that the 1 mil shielded cells actually lost less power in 418 days than did the 60 mil shielded cell. The 6 mil shielded cells degraded the least, not only as compared to the other 10 cells here reported on, but the least of all 30 cells in the experiment.

Fig. 6 has been plotted in the customary semi-log manner, in which coordinates "true" radiation damage (loss of minority carrier lifetime throughout the cell) results in a straight line plot for power losses greater than about 15 percent. The fact that Fig. 6 uses such coordinates should not be taken as indicating that the solar cell damage here observed is believed to be wholly "true" radiation damage. As indicated above, it appears that a decrease in illumination and an increase in series resistance occurred. These do not qualify as "true" radiation damage.

#### Hypotheses

It is not definitely understood, at this time, why, on ATS-I, the solar cell damage was so great or why the optimum shield thickness (for maximum power) was about 6 mils (or, more literally, between 1 and 15 mils).

In order to account for the shapes of the voltage-current curves we have, in the "Discussion" invoked some particle damage, some decrease in illumination, and some introduction of series resistance. We here offer some hypotheses to account for these effects.

Concerning particle damage, it must suffice here to say that solar power supply designers for synchronous spacecraft have considered that a power degradation of from 2 to 4 percent per year (for a few years) is to be expected, as a consequence of the known particle environment, for cells shielded with shields of from 10 to 30 mils thickness. This value may be compared with a yearly rate, in this experiment, of 6.6 percent for 6 mil shielded cells and 14.4 percent for 60 mil shielded cells.

It thus appears that perhaps half of the damage to the 6 mil shielded cells was caused by particle irradiation. The remainder is best accounted for by a decrease in illumination.

Since a decrease in the sun's intensity and shadowing effects appear equally and highly unlikely in this experiment, one must invoke some mechanism associated with the solar cell. An obvious suspect is darkening of the shield material. For shields of 6 mils or greater

the material was an ultraviolet resistant, highly pure form of artificial fused silica, Corning type 7940. Several investigators, including Haynes and Miller,<sup>13</sup> have tested a number of potential radiation shield materials for darkening under electron irradiation. They found that a fluence of  $10^{16}$  1.2 MeV electrons per  $\text{cm}^2$  (which is much greater than could have obtained in this flight experiment) on a Corning type 7940 silica (60 mils, coated with blue reflecting, and anti-reflecting films) showed no significant loss in transmission in the spectral region to which silicon solar cells respond. They also found that pure synthetic crystalline sapphire was extremely darkening resistant. It is significant, in discounting radiation darkening in this space experiment, that a pair of solar cells was included in it whose 30 mil shields were made of this material, supported with no adhesive (a la Telstar), and with no coatings, and these cells also showed degradation. These facts support the presumption that the illumination diminution evidently present with the ATS-I experimental cells was caused neither by shield darkening, loss of optical coatings, nor darkening of adhesives.

The illumination of the solar cells of this experiment effectively changes with solar aspect angle. The maximum correction (based on pre-flight calibration) was 9 percent. If the correction functions were incorrectly determined or applied then an apparent, false variation in illumination with time would have been introduced. The daily plots of cell short-circuit current show no cyclic variations as would have been introduced by such incorrect aspect angle corrections.

It has been suggested that the cells of this experiment, as well as those of the main solar array on ATS-I, were contaminated by the gas ejected to "spin-up" the spacecraft early in its flight. Such contamination might have decreased the cell illumination. However, the gas was nitrogen, which is an unlikely contaminant, unless very impure. It is still possible that the later firing of the final rocket motor, or the firing of the hydrogen peroxide station keeping jets might have caused a surface contamination of the solar cells.

Finally, micrometeoroid erosion of the shield surface may be considered. This causes a small drop in effective illumination. However, the micrometeoroid population is relatively great only near the earth, and such an influence at 22,240 miles is considered very unlikely.

Thus, a completely rational explanation of the required illumination decrease, required by these results, cannot be said to have been found. Surface contamination appears most likely.

It will be recalled that inspection of the voltage-current curves required the development of series or, possibly, shunt resistance. Further, it was required that the damage mechanism be such that thick shields aggravated the appearance of this quantity.

Now, if one imagines that the space environment at synchronous altitude had a proton content whose spectrum consisted of, substantially, an intense component of about 4 MeV and one of about 25 MeV one of the required effects might be accounted for. In agreement with the space experiment large damage would occur to unshielded cells. A one mil shield would cause a great decrease in damage. Increasing the shield to 6 mils would further decrease the damage by almost completely removing the low energy proton component. Further increases in shield thickness would decrease the energy of the high energy component, but would make them more effective damage agents for the solar cells. This trend would fit the observations. However, proton damage over the whole cell is not particularly selective in increasing series resistance or in concentrating its influence on the maximum power region of the cell characteristic, as is required. Thus, this hypothesis not only entails a proton spectrum in disagreement with measurements but it also is not satisfactory on other grounds.

An obvious candidate for suspicion of contributing series resistance is degradation of contacts on the cells. In the cells here reported on the contact material was silver-titanium, sintered to the cell surface. The cells were not solder-dipped.

There have been numerous reports that some non-solder dipped solar cells, shielded or unshielded, suffer contact deterioration when stored at a moderately elevated temperature and humidity. According to Barbera<sup>14</sup> a large fraction of the contact material of a bare cell often, with time, becomes completely detached from the cell. If the shields of shielded cells are removed the contact strips are often found to have little adhesion to the cell surface. Moderately degraded cells showed little loss in short-circuit current on open-circuit voltage, but there was a large power loss, characteristic of series resistance. Although studies are incomplete it appears that storage at low humidity and moderate temperature greatly retards the deterioration. The latter consideration reduces the probability that this mechanism contributed the series resistance damage component observed in the ATS-I space experiment. It may be conjectured that since only small effects of this nature are required a sufficient degree of this type of deterioration continued after launch to provide the indicated effect. However, it remains to account for the manner in which increasing the shield thickness apparently accelerated such deterioration. Thus, deterioration of the contacts, while attractive in some respects, does not completely fulfill the requirements for introduction of series resistance, in this experiment.

Abnormal radiation damage effects associated with low energy proton irradiation through and adjacent to the "bar" of the upper contact pattern of a solar cell have been reported. The type of cell here considered utilized, as contact material, a silver-titanium layer, sintered to the cell surface. The cells were not solder-dipped. The

bar was about 0.1 cm wide, along the 2 cm edge of the cell. The shield nominally abutted the bar edge, leaving little cell area unshielded, as judged by post-flight examination of shielded cells fabricated by the same technician who mounted the cells of this experiment. However, other small unshielded areas around the edges could be found. The upper contact lead was made of a strip of 2 mil thick expanded silver mesh, soldered to the entire length of the contact bar. The lead plus solder thus presumably constituted an effective shield against low energy protons for the major part of the bar area.

A note<sup>15</sup> has appeared concerning the radiation damage that may occur when shielded solar cells having upper contacts of thin films of titanium-silver alloy are exposed to protons whose energies are greater than a few hundred KeV. Such protons penetrated the contact material. They had little effect on short-circuit current, a strong effect on maximum power, and a moderate effect on open-circuit voltage. These are the characteristics of a shunt resistance. That this damage mechanism was operative in the ATS-I experiment seems unlikely because, as described above, the bar contact was shielded by the soldered lead. Also this mechanism, involving shunt resistance, introduces more open-circuit voltage damage than is believed occurred in flight. Further, the required relation to shield thickness is not apparent.

Brucker<sup>16</sup> et al., have reported that abnormally large damage is caused by exposing a narrow strip (one to four percent of the cell area) adjacent and parallel to the contact bar to protons of 200 KeV energy. Both short-circuit current and open-circuit voltage were little affected, but a significant reduction of maximum power occurred. It is not evident whether or not the contact area was opaque to the protons. This effect is of the nature required as a damage component to explain the curve shape of the damaged, heavily shielded cell (Fig. 4). However, more studies of low energy proton damage to contact areas and areas adjacent thereto, with careful control of all known variables, is greatly to be desired.

As a final hypothesis, it is suggested that the use of increasingly thicker shields altered (as by scattering) the geometry of the low energy proton irradiation of the various small unshielded areas of the solar cells so as to not only cause abnormal damage in the maximum power region, but to cause it to become greater with shield thickness. Such a damage component, together with the increasing protection provided over the main area of the cell from electron damage, and with a current loss in all cells, caused by surface contamination, could have caused the current, power, and voltage degradations to vary with shield thickness in the observed manner.

Obviously, more laboratory and flight experiments are required to positively judge the validity of the above hypotheses.

To avoid the excessive synchronous orbit solar cell damage observed in this experiment, and evident also in the main solar arrays of ATS-I and certain other

synchronous spacecraft, it is suggested, (a), that the cells be of 10 ohm-cm silicon, boron-doped, with solder-dipped contacts; (b), that the shields be of Corning type 7940 UV resistant, fused silica, approximately 6 mils thick; (c), that the shields be oversize, so as to cover all the cell area except that necessary for connecting leads. It is recognized that the use of such solder-dipped cells with oversize shields (or some other "fix") may so alter the relative effect of the various damage mechanisms that shields thicker than 6 mils would then be effective in protecting the power-producing capability of the cell from damage.

## CONCLUSIONS

In summarizing the conclusions to be drawn thus far from the ATS-I solar cell radiation damage experiment, it will be assumed that the received data was accurate (noise and calibration drift were negligible), that the corrections were properly applied (as noted, corrections never exceeded nine percent), the calculations were accurate (for this report they were made under close supervision), and the voltage-current curves were properly drawn (there is only slight opportunity for variation when eight data points, well spaced, are available). It will also be assumed that the solar cells used were representative (they were not laboratory specimens, but were made by commercial manufacturers), that the cells were properly mounted (the work was done by a technician experienced in the field) and that there was no spurious noise introduced (the data is very regular and repetitive, ground loops were studiously avoided, the calibration supply was separate and floating, and the drift in the spacecraft electronics over 416 days was barely detectable).

Under the above assumptions the data here reported support the following conclusions, all involving silicon, 10 ohm-cm, n-on-p solar cells with various shields of Corning 7940 silica, as observed over 416 days in synchronous orbit:

(1) The solar cell degradation was greater than that expected from the particle environment.

(2) Unprotected solar cells degraded significantly during 3 passages through the radiation belts during the launch procedure; at 416.8 days after lift-off their maximum power ( $P_M$ ) was 11.4 percent initial value, short-circuit current ( $I_{sc}$ ) was 42.0 percent, open-circuit voltage ( $V_{oc}$ ) was 55.0 percent, and curve factor ( $F$ ) was 0.344.

(3) For 1 mil (7740 glass) shielded cells  $P_M = 84.9\%$ ,  $I_{sc} = 90.1\%$ ,  $V_{oc} = 97.2\%$ ,  $F = 0.699$ .

(4) For 6 mil shielded cells,  $P_M = 92.5\%$ ,  $I_{sc} = 91.7\%$ ,  $V_{oc} = 98.9\%$ ,  $F = 0.739$ .

(5) For 15 mil shielded cells,  $P_M = 88.7\%$ ,  $I_{sc} = 92.7\%$ ,  $V_{oc} = 98.7\%$ ,  $F = 0.692$ .

(6) For 30 mil shielded cells,  $P_M = 86.9\%$ ,  $I_{sc} = 92.6\%$ ,  $V_{oc} = 98.7\%$ ,  $F = 0.683$ .

(7) For a 60 mil shielded cell,  $P_M = 83.5\%$ ,  $I_{sc} = 93.9\%$ ,  $V_{oc} = 98.3\%$ ,  $F = 0.660$ .

(8) The degradation in power of the more heavily shielded cells was relatively large compared to degradation in short-circuit current or open-circuit voltage.

(9) The above conclusion points to a damage mechanism (among others) in which series resistance developed within the cell, possibly at the unshielded areas near contacts, by some action not ordinarily considered in radiation damage studies.

(10) Cells bearing 6 mil shields degraded, in power, less than cells bearing either thicker or thinner shields.

(11) Thicker shields were effective in protecting the cells against degradation in short-circuit current.

(12) Short circuit current was not a valid indicator of solar cell damage under the conditions of this experiment.

(13) To qualitatively account for the shape of the various voltage-current curves it is necessary to postulate various combinations of, (a), illumination decrease; (b), particle radiation damage; and, (c), a mechanism introducing large power losses in the maximum power region, for heavily shielded cells.

(14) A continued study of solar cell damage both in theory and by laboratory and space experiments is advisable, since questions of both scientific and economic importance have been raised.

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Table I  
ATS-1 Solar Cell Properties at Various Times

D = 1 au  
T = 24.4°C  
 $\theta = 90.0^\circ$

1	2	3	4	5	6	7	8	9	10	11
Cell No.	Shield Material	Shield Thickness (mils)	Time After L.O. (days)	$I_{sc}$ (ma)	$V_{oc}$ (mv)	$P_M$ (mw)	F	$I_{sc}$ %	$V_{oc}$ %	$P_M$ %
25,26	None	0.0	0.064	70.3	548.3	26.7	0.694	100.0	100.0	100.0
		0.0	3.28	61.5	425.8	16.9	0.644	87.6	77.7	63.0
		0.0	20.3	(55.0)	330.6	10.3	(0.566)	(78.3)	60.3	38.5
		0.0	100.7	(44.5)	311.9	6.3	(0.458)	(63.4)	56.9	23.8
		0.0	270.4	(34.5)	305.1	4.0	(0.383)	(49.2)	55.7	15.0
		0.0	416.8	(29.0)	301.6	3.1	(0.349)	(41.4)	55.0	11.4
15,16	7740 Glass	1	0.064	62.4	544.0	24.5	0.722	100.0	100.0	100.0
		1	3.28	61.6	540.0	24.4	0.735	98.7	99.3	97.6
		1	20.3	60.8	538.7	23.8	0.729	97.4	99.0	97.4
		1	100.7	59.0	536.8	22.0	0.694	94.5	98.7	89.6
		1	270.4	57.2	531.8	21.4	0.702	91.7	97.8	87.4
		1	416.8	56.2	528.8	20.8	0.699	90.1	97.2	84.9
5,6	7940 Silica	6	0.064	67.9	558.7	27.5	0.724	100.0	100.0	100.0
		6	3.28	67.0	560.3	28.1	0.749	98.6	100.3	102.1
		6	20.3	65.9	559.5	27.3	0.743	97.0	100.2	97.7
		6	100.7	64.9	555.4	26.2	0.727	95.6	99.4	95.5
		6	270.4	63.2	552.5	25.6	0.736	93.0	98.9	93.5
		6	416.8	62.2	552.4	25.4	0.739	91.7	98.9	92.5
23,24	7940 Silica	15	0.064	67.7	560.0	27.1	0.714	100.0	100.0	100.0
		15	3.28	67.9	563.0	28.1	0.736	100.4	100.2	103.5
		15	20.3	66.4	560.3	26.3	0.707	98.2	99.7	96.9
		15	100.7	65.4	557.6	25.9	0.709	96.7	99.3	95.2
		15	270.4	63.8	555.6	25.0	0.704	94.4	98.9	91.9
		15	416.8	62.7	554.6	24.1	0.692	92.7	98.7	88.7
21,22	7940 Silica	30	0.064	69.6	558.8	28.0	0.719	100.0	100.0	100.0
		30	3.28	69.1	561.2	28.2	0.729	99.3	100.5	101.1
		30	20.3	67.6	555.7	26.9	0.715	97.2	99.5	96.1
		30	100.7	66.5	554.1	25.9	0.704	95.6	99.2	92.7
		30	270.4	65.6	554.0	25.2	0.695	94.4	99.2	90.3
		30	416.8	64.5	551.3	24.3	0.683	92.6	98.7	86.9
20	7940 Silica	60	0.064	69.2	563.1	28.4	0.729	100.0	100.0	100.0
		60	3.28	68.6	564.0	28.2	0.729	99.1	100.2	99.3
		60	20.3	68.2	560.1	27.0	0.707	98.6	99.5	95.1
		60	100.7	66.9	557.5	25.4	0.681	96.7	99.0	89.4
		60	270.4	66.1	559.4	24.4	0.660	95.5	99.3	85.9
		60	416.8	65.0	553.5	23.8	0.660	93.9	98.3	83.5



ATS-I, CELL 25  
I/V VERSUS TIME

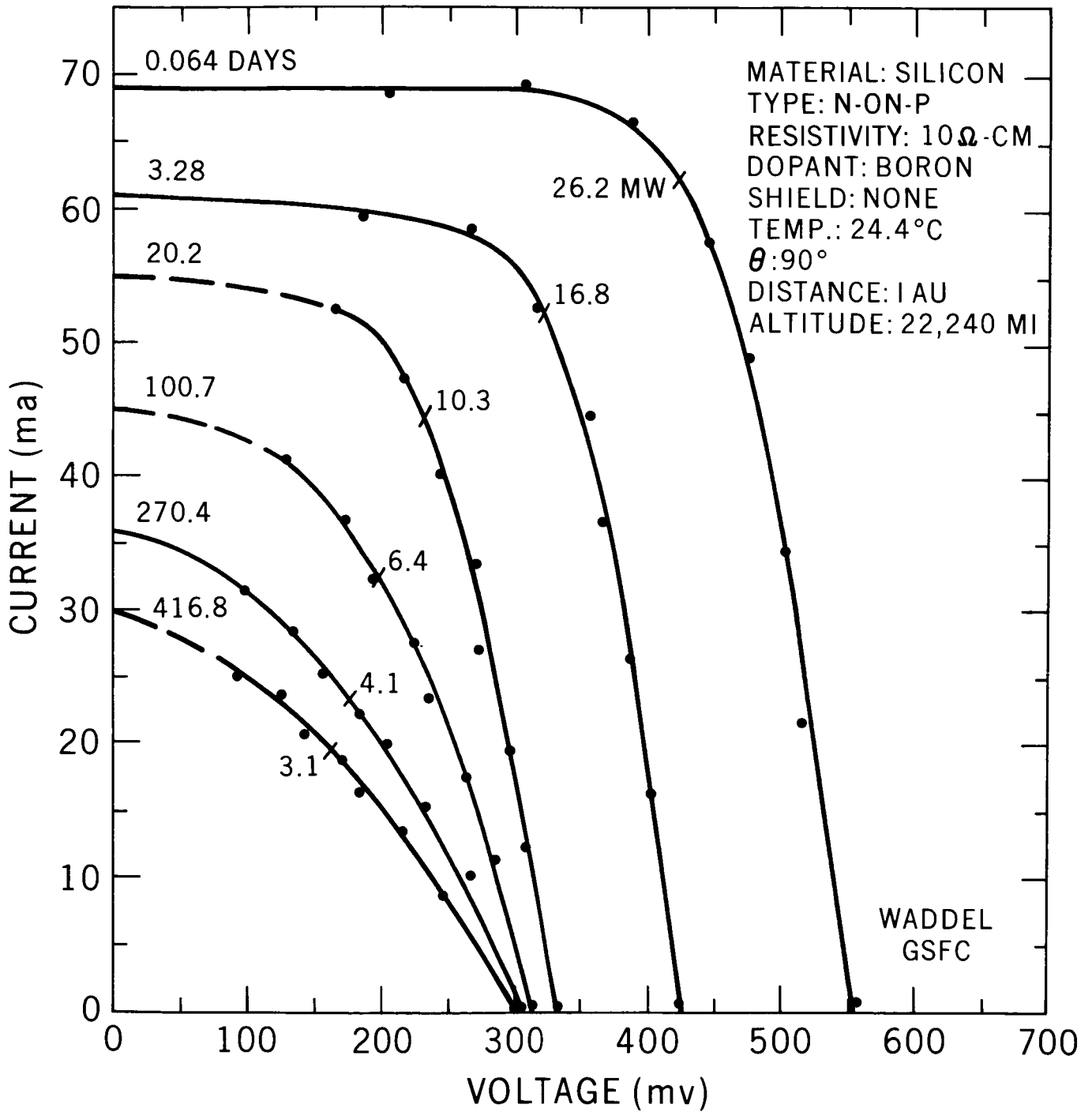


Figure 1 - A voltage-current family for unshielded cell  
No. 25.

# ATS-I, CELL 15(•), 16(▲)

## I/V VERSUS TIME

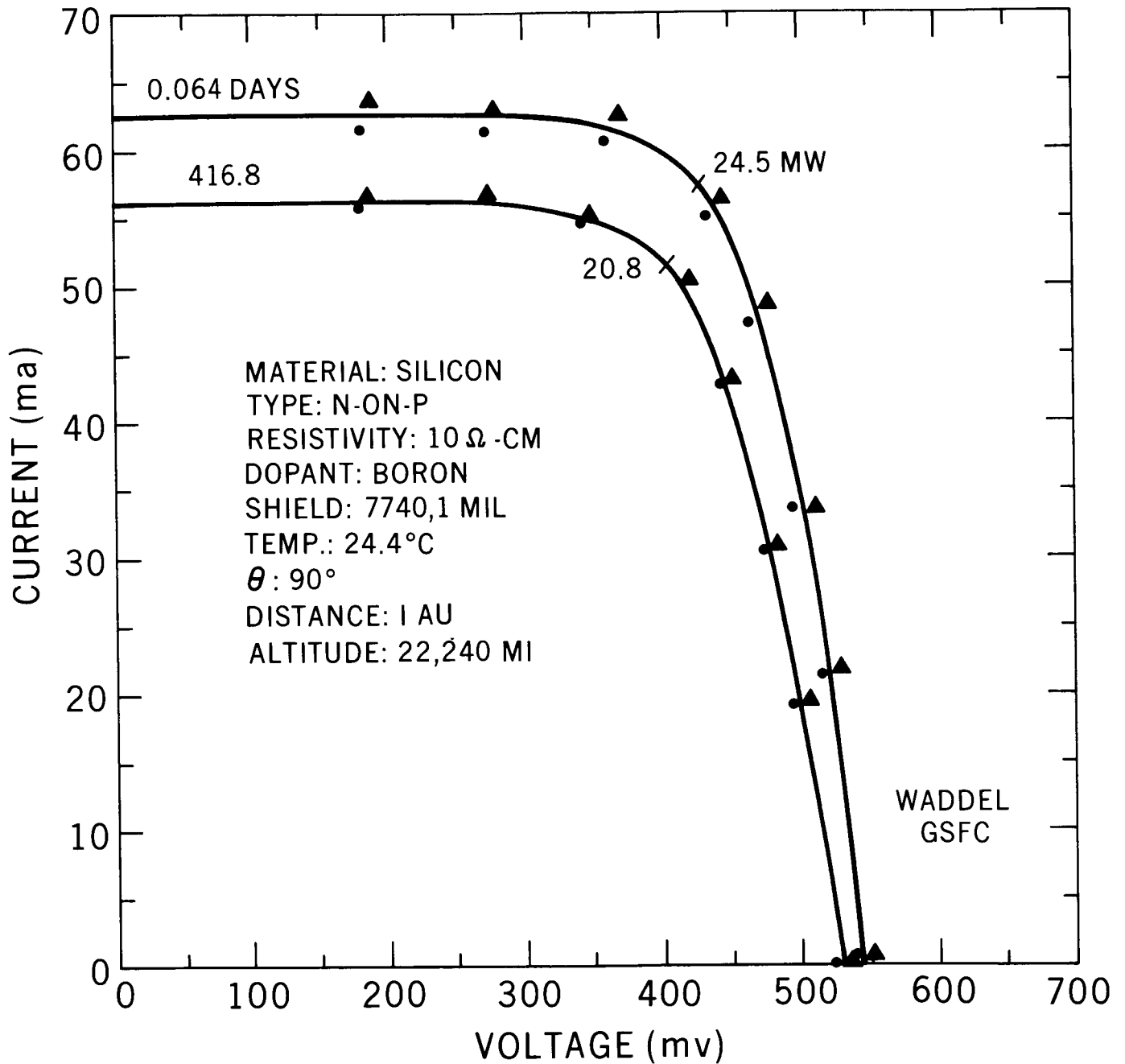


Figure 2 - Voltage-current curves for cells 15 and 16, with 1 mil integral glass (7740) shields.

ATS-I, CELL 5  
I/V VERSUS TIME

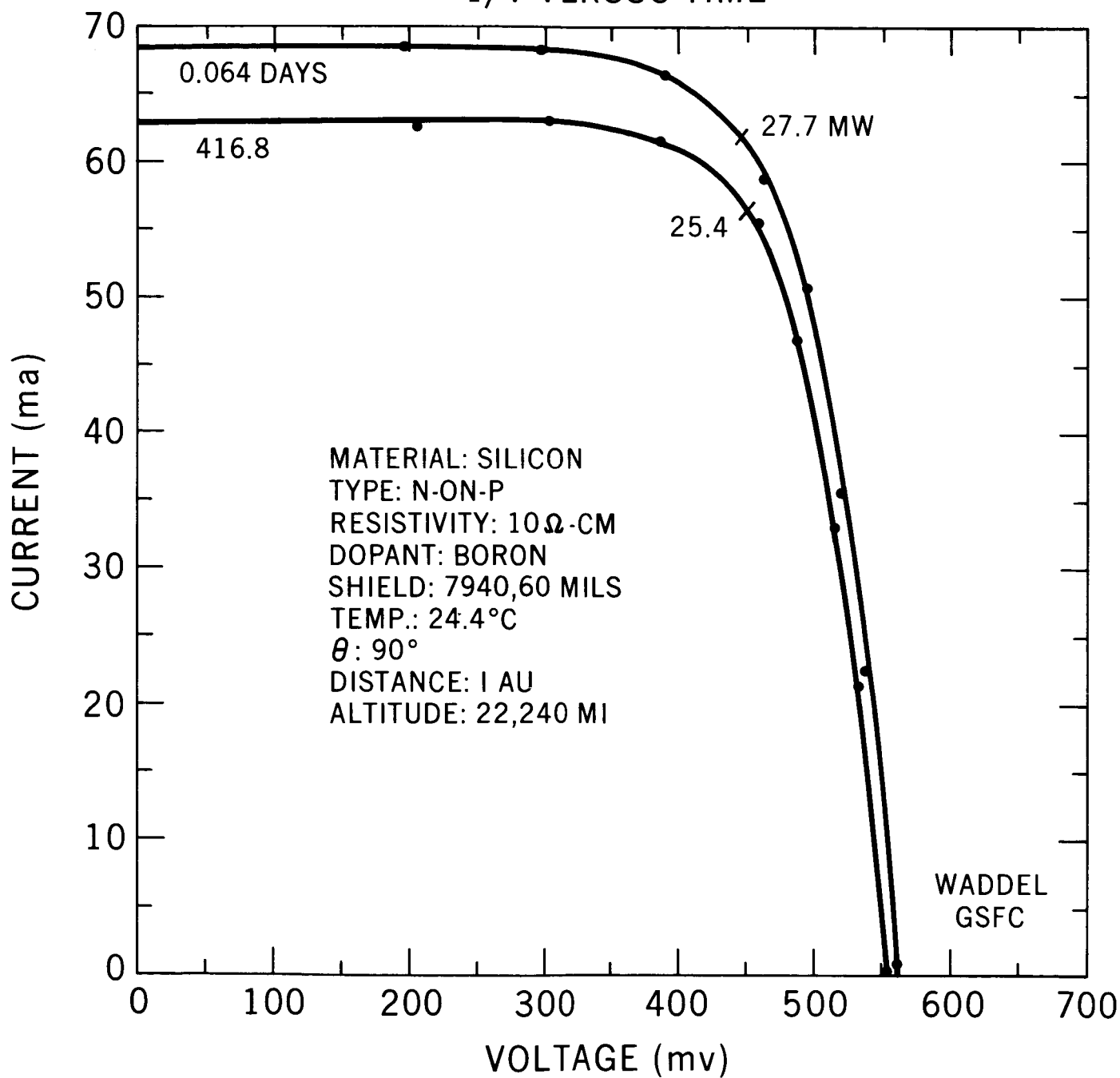


Figure 3 - Voltage-current curves for cell 5, with a 6 mil silica (7940) shield.

ATS-I, CELL 20  
I/V VERSUS TIME

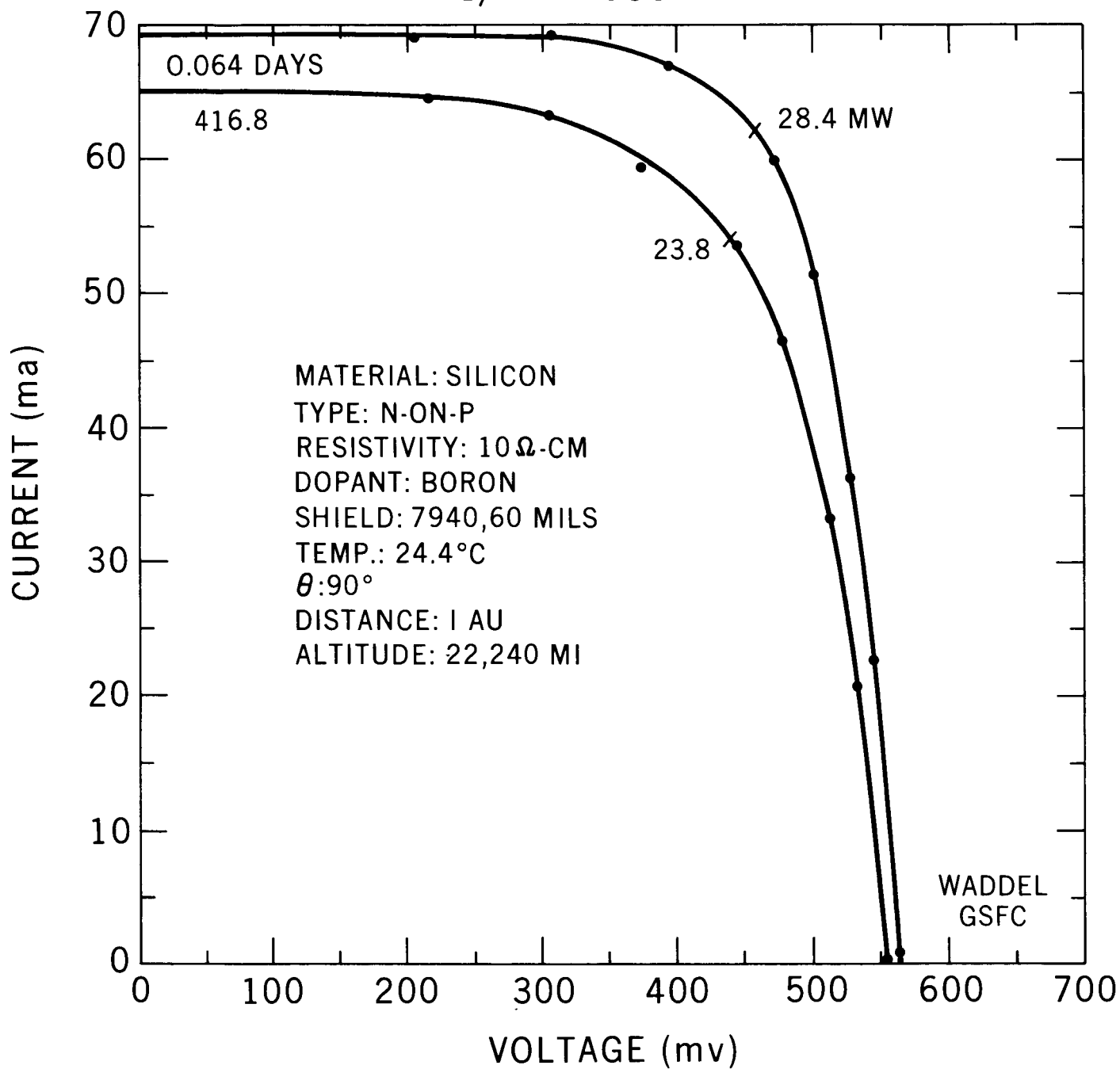


Figure 4 - Voltage-current curves for cell 20, with a 60 mil silica (7940) shield.

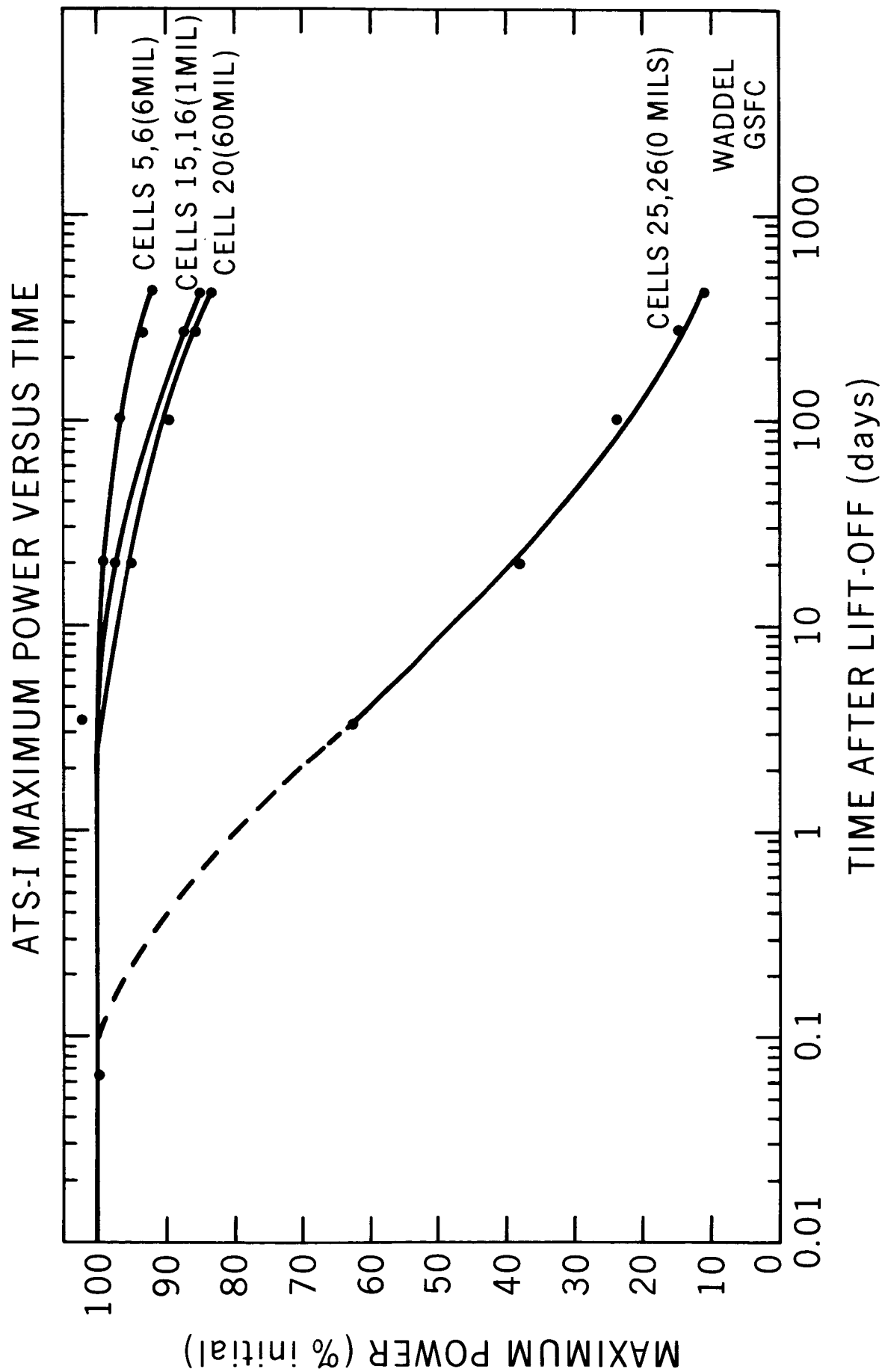


Figure 5 - Maximum power versus time for several cells with various shields.

ATS-I  
SOLAR CELL PROPERTIES AT 416.8 DAYS  
VERSUS SHIELD THICKNESS  
10  $\Omega$ -CM N-ON-P

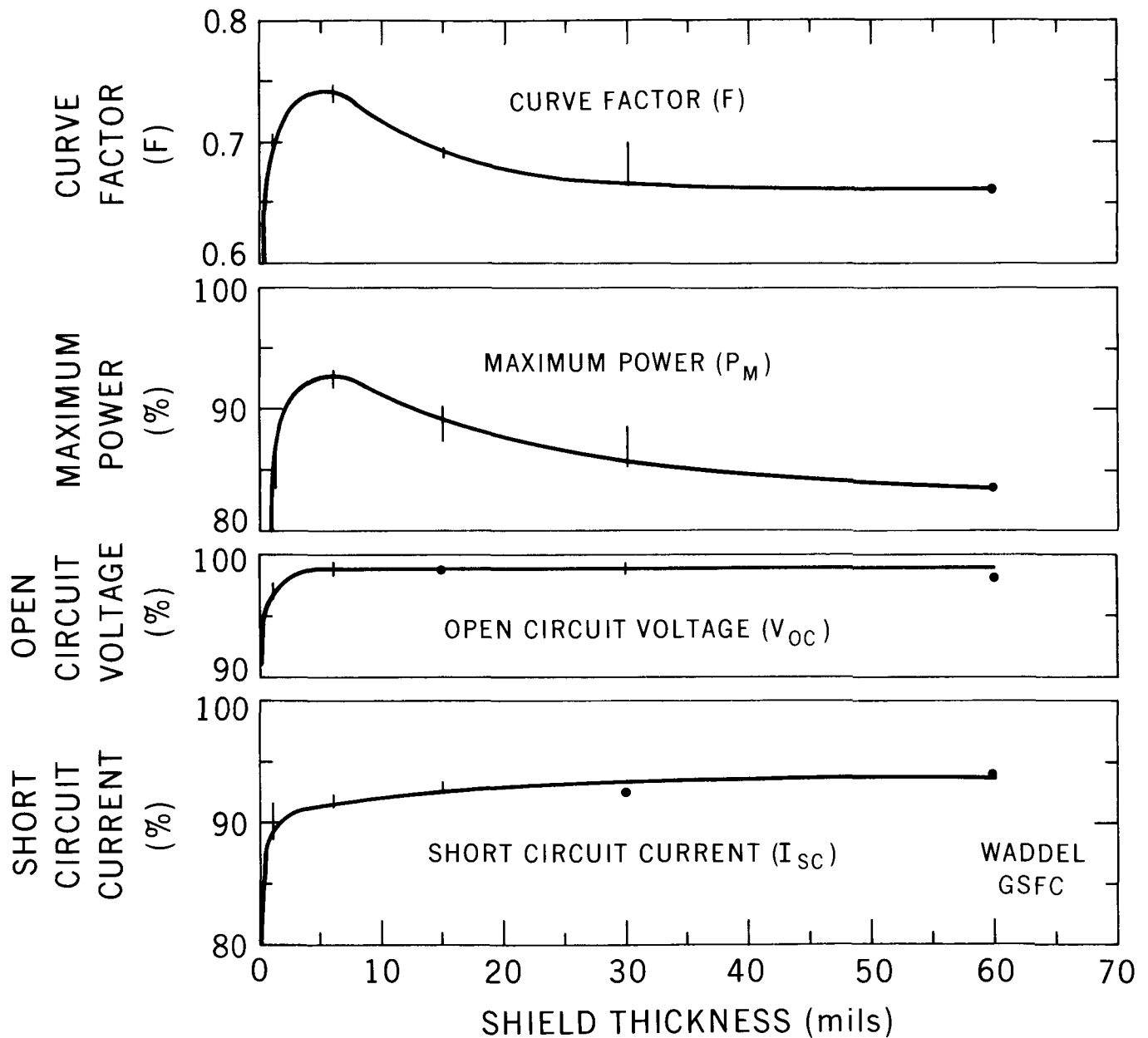


Figure 6 - Curve factor (F), maximum power ( $P_M$ ), open-circuit voltage ( $V_{OC}$ ), and short-circuit current ( $I_{SC}$ ) versus shield thickness, at 416 days after lift-off.